Municipal incinerated bottom ash characteristics and potential for use as aggregate in concrete

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TITLE: MUNICIPAL INCINERATED BOTTOM ASH CHARACTERISTICS AND POTENTIAL FOR USE AS AGGREGATE IN CONCRETE

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ABSTRACT

The use of municipal incinerated bottom ash (MIBA) as aggregate in concrete applications has been assessed through the analysis and evaluation of the globally published data. After appropriate pre-treatments, MIBA can be used as fine or coarse aggregate in mortar, concrete and blocks. Full-scale operations have been undertaken with success, mainly in blocks. MIBA lightweight aggregate had similar properties to Lytag, though with marginally lower strength. Concrete containing MIBA lightweight aggregate achieved low density, high consistence properties, with strengths just below Lytag mixes. Replacing sand in foamed concrete, MIBA mixes satisfied the high flowability, low strength requirements.

Key Words: Municipal incinerated bottom ash, sustainable construction materials, aggregate, mortar, concrete, blocks, lightweight aggregate concrete, foamed concrete

HIGHLIGHTS

- Global data on MIBA as aggregate in concrete analysed and evaluated
- MIBA use as fine or coarse aggregate in mortar, concrete, blocks, foamed mixes
- Lightweight aggregate produced using MIBA and subsequently used in concrete

1. INTRODUCTION

Municipal incinerated bottom ash (MIBA) is the main residue resulting from the incineration of municipal solid waste (MSW). As waste management continues to move away from landfilling, incineration is becoming an increasingly important treatment option. The process involves the recovery of energy from the waste combustion and results in large reductions in the quantity of material to manage, decreasing by approximately 70% by mass - of which 80-90% is bottom ash and the remainder is fly ash and air pollution control residues.

Annual MSW production rates of 241 MT in the 28 European Union countries (Eurostat, 2016 – data from 2014), 654 MT in the 34 OECD countries (OECD, 2016 – data from 2014) and 1,840 MT worldwide (Waste Atlas, 2013 – data from 2012) have been reported. Data for MIBA production is limited, though in the European Union, 27% of the MSW was reported to be incinerated (Eurostat, 2016 – data from 2014) and on this basis, it is estimated that 16 MT of bottom ash are generated per annum.

The quantity of MIBA produced presents a significant management problem, however as a useful secondary resource for potential use in construction, the material offers great opportunity. European countries such as Belgium, Denmark, Germany and The Netherlands are taking advantage of this potential, using 100, 98, 86 and 80% of the MIBA produced, respectively, predominantly as fill and road construction materials (An et al., 2014; Qing and Yu, 2013). Around half of the MIBA generated in the UK is used in construction, including as an aggregate in concrete blocks (Dhir et al., 2011, ISWA, 2006, Qing and Yu, 2013).

The use of MIBA in concrete related applications is an area where there has been a strong research interest, yet the practical application is not as far progressed as its use in road pavements. Concrete is recognised as one of the most widely used construction materials, though carries a high carbon footprint, with cement production accounting for around 8% of the global CO_2 emissions (Netherlands Environmental Assessment Agency, 2015). With increasing emphasis on sustainable development, major changes are required to reduce the emissions associated with cement production and conserve natural materials through the incorporation of secondary and recycled materials in concrete. The characteristics of MIBA suggests that it has potential for use as both aggregate and cement (in ground form) components in concrete, offering a high value use of the ash, though typically with onerous material requirements. Its use as aggregate as a substitute for natural sand and gravel in concrete related applications is the particular focus of this paper.

2. THE PROJECT

This project examines the characteristics of MIBA and its potential for use as an aggregate in concrete related applications through the analysis and evaluation of the global experimental results. The aim is to establish current status of the material and advance its safe and sustainable use as both coarse and fine aggregate components in a range of applications: mortar, concrete, masonry blocks, lightweight aggregate concrete and foamed concrete.

The data was managed in two parts, with the first dealing with the characteristics of MIBA. Results on the material properties were provided as a matter of routine in a huge number of studies, which explored the use of MIBA in all types of construction applications. To avoid overwhelming the messages in the text, those references containing solely numerical data on characteristics of MIBA were listed in the supplementary data. The second part of the data is on the use of MIBA specifically as an aggregate in concrete related applications. This research on concrete has been published over a time period of 40 years and carried out in 18 countries across Europe, Asia and North America (Figure 1). Beginning in 1979, this research was produced intermittently up until the late 1990s, after which the rate of publication increased and in particular, a large amount of work has been undertaken in the last three years. Over half of the work has originated in Europe, whilst the largest individual contributions have come from the UK, USA and Taiwan.

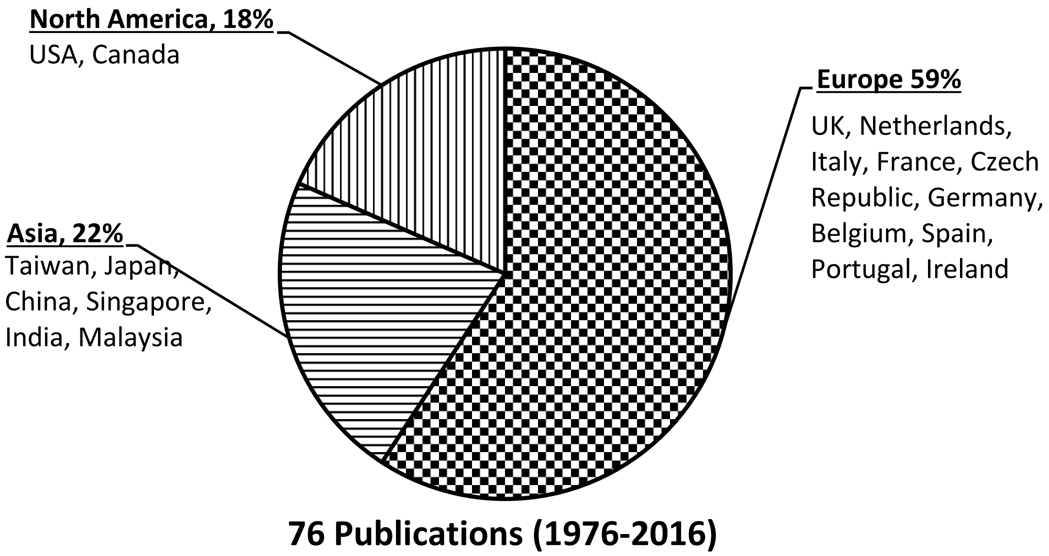

Figure 1: Continental and country-wise distribution of publications on MIBA in concrete applications

3. MATERIAL CHARACTERISTICS

3.1 Grading

As-produced MIBA contains metallics, ceramics, stones, glass fragments and unburnt organic matter, with particles sizes ranging up to 100mm, though the oversized fraction, 30/40/50mm, is customarily removed as part of a standard screening process. Further changes to the grading of MIBA arise from the subsequent processing adopted, depending on the plant operation and end-use of the material. This has included further sieving, grinding, ferrous and non-ferrous removal, size separation, thermal and chemical treatment.

Particle size distribution curves are presented in Figure 2 for MIBA samples used in concrete related applications that were screened or sieved as an aggregate component (references in Appendix A), along with the grading curves for the BS EN 12620 (2013) fine aggregate limits.

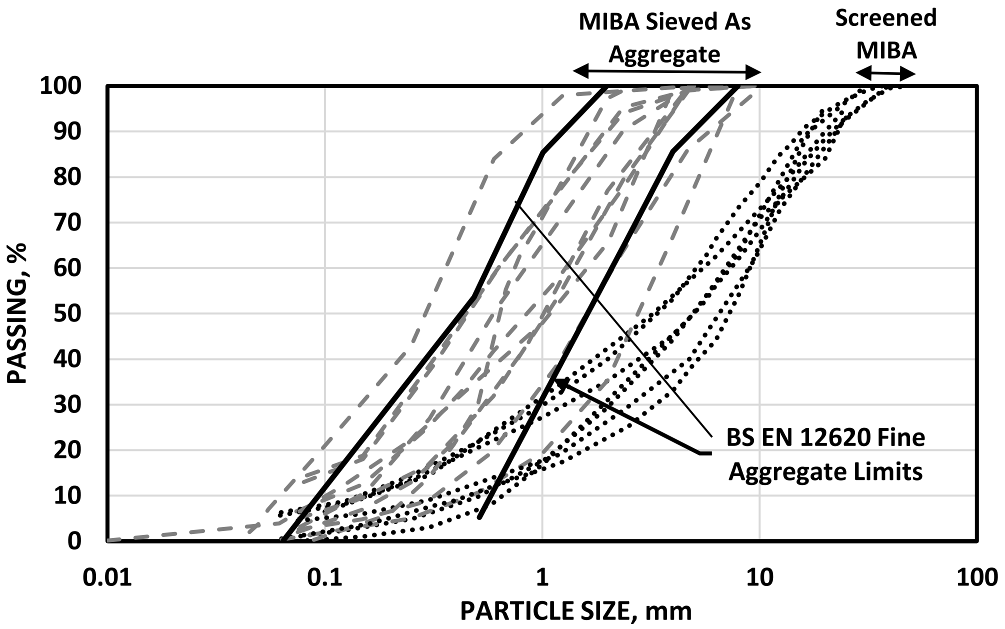

Figure 2: Particle size distribution of screened, sieved and ground MIBA

Screened MIBA samples are shown to be well graded, containing mostly sand and gravel sized particles, with a low silt fraction. The grading of MIBA was most commonly adjusted by removing the gravel fraction in sieving to produce a suitable fine aggregate component.

3.2 Density

The material has been found to have an average specific gravity of 2.32, based on the total data (references in Appendix B) and this categories the material as less dense than typical values of 2.65 for natural sand, though above the 2.15 value of furnace bottom ash (Torii and Kawamura, 1991). Bulk density results ranged from 510-2283 kg/m^3, with an average value of 1400 kg/m^3 (14 samples. Appendix B), which is comparable to loose sand (Jackson and Dhir, 1996).

As presented in Figure 3, the density MIBA samples can also be further sorted into three groups based on how the material is processed:

(a) Samples screened or unspecified processing – Average specific gravity of 2.37, with most in the range from 2.2-2.5.

(b) Samples sieved as fine aggregate – Average specific gravity of 2.34, though most samples had lower densities than category (a) samples. Additional results given per size fractions of the MIBA samples (Forth et al., 2006; Ginés et al, 2009; Hu et al., 2010; Tang et al., 2015; Wu et al., 2016a) supported the finding that the fine fractions of MIBA are less dense than the coarse fractions .

(c) Samples subjected to metal recovery treatment such ferrous and non-ferrous metal removal and washing - Decrease in the density is evident, average specific gravity of 2.2, due to a reduction in the heavy elements such Al, Cu, Fe and Pb. The higher specific gravity of two samples in this group (2.47 and 2.65) can be attributed to additional grinding treatment, which reduced porosity and increased density.

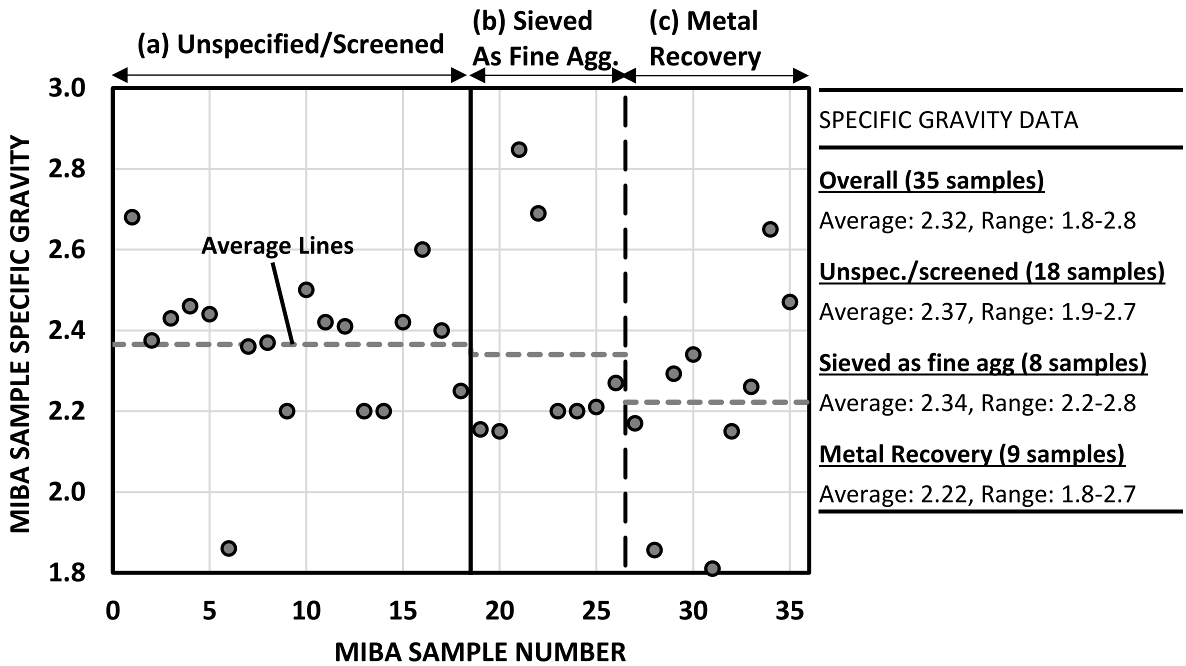

Figure 3: Specific gravity of MIBA samples subjected to (a) screening or unspecified treatment, (b) sieved as fine aggregate, (c) metal recovery treatment.

3.3 Morphology

Municipal incinerated bottom ash has been found to contain irregular, angular shaped particles with a porous microstructure, formed from the heating and cooling during incineration (references in

Appendix C). The irregularity and resultant higher specific surface area, combined with high absorption properties associated with high porosity, suggest that the material may have high water demand when used in concrete applications.

3.4 Water Absorption

In agreement with the morphological properties, high water absorption results have been reported for MIBA, ranging from 2.4 – 15.0%, with an average value of 9.7% (references in Appendix D). The absorption properties of the material are substantially higher than natural sand which is typically 1-3% (Neville, 1995). Further comparisons of fine and coarse fractions of MIBA showed that the fine fraction generally had higher absorption values due to the greater specific surface area (Hu et al., 2010; Izquierdo et al., 2002; Keulen et al., 2016; Liu et al., 2014; Siddique et al., 2010).

3.5 Oxide Composition

The main oxides present in MIBA are SiO_2 (average content of 37.5%), CaO (22.2%) and Al_2O_3 (10.3%) and others such as Fe_2O_3 (8.1%), Na_2O (2.9%), SO_3 (2.4%), P_2O_5 (2.4%), MgO (1.9%) and K_2O (1.4%) also appear in smaller quantities (references in Appendix E).

For MIBA use in concrete, the sulfate content, measured in form of SO_3, is a particularly important constituent that may potentially lead to deleterious expansive behaviour in a cement environment. As a useful benchmark, EN 450 (1995) specifies a 3% SO_3 limit for the use of coal fly ash as a cementitious component in concrete. With an average SO_3 content of 2.4%, the contribution of MIBA as an aggregate to the overall sulfate levels may need to be considered. Magnesium can also affect the soundness of concrete mixes, though the content present in MIBA is low.

3.6 Loss On Ignition

The bottom ash was found to have an average loss on ignition (LOI) of 5.8% (references in Appendix F). There is quite a high degree of variation in the LOI data, with a coefficient of variation of 71%, contributed by a number of very high LOI values reaching up to 17.5%. Residual organic matter can compromise the integrity and strength of the material. As such, treatment of the material may need to be considered for MIBA samples with high LOI values, before it can be effectively used in concrete.

3.7 Mineralogy

Quartz has been identified as the most abundant mineral present in MIBA, along with the commonly found calcite, hematite, magnetite and gehlenite and a large variety of other less frequently found silicates, aluminates, aluminosilicates, sulfates, oxides and phosphates (references in Appendix G). Along with high intensity crystalline peaks in the X-ray diffraction results, amorphous phases have also been recognised in MIBA. Glass contents ranging from 15-70% (Bayuseno and Schmahl, 2010; Paine et al, 2002; Rubner et al., 2008 and Wei et al., 2011) have been reported for MIBA.

3.8 Element Composition

As presented in Table 1, Si, Ca, Fe and Al are the most abundant elements present in MIBA. Additional toxic elements such Zn, Cu, Pb, Cr, Ni, Cd and As are present in lower quantities and are most critical to consider during the environmental assessment of the leaching risks.

The issue of the metallic aluminium in MIBA leading to the formation of hydrogen gas in an alkaline cement environment, has been flagged as an important concern (Tyrer, 2013; Pecqueur et al, 2001; Muller and Rubner, 2006; Rubner et al, 2008; Weng et al, 2015). The associated expansive reactions can compromise the strength and durability performance in concrete, with the exception of lightweight applications such as foamed concrete, where the expansive reaction can be desirable. As such, lower metallic Al contents in MIBA are favoured.

Table 1: Element composition of MIBA (references in Appendix H)

ELEMENT	SAMPLE NO.	AVERAGE, mg/kg	S.D. mg/kg	CV, %
Si	13	210893	64046	30
Ca	31	117750	59238	50
Fe	36	53455	36393	68
Al	35	44047	15634	35
Na	24	22812	16526	72
Mg	29	14967	8664	58
Cl	37	8944	9443	106
K	29	8256	4716	57
Ti	12	6632	5553	84
S	27	5184	2208	43
P	10	4866	3987	82
Zn	78	4044	2974	74
Cu	76	3071	2796	91
Pb	73	1641	1205	73
Ba	31	1312	910	69
Mn	41	921	599	65
Cr	77	398	325	82
Sr	17	379	179	47
Sb	18	253	714	282
Ni	58	182	132	73
V	22	167	286	172
Co	24	50	104	207
As	46	50	61	123
Mo	19	28	27	99
Cd	50	14	23	159
Hg	17	1.4	4.0	290

S.D - standard deviation; CV - coefficient of variation

The ash was found to have an average chloride content of 0.9% (references in Appendix H), mainly arising from polyvinylchloride plastic in the waste (Wu et al., 2016b). This significant chloride presence in MIBA suggests that it will be important to consider when calculating the total chloride ion content of all constituents in reinforced concrete. Treatment of MIBA may be necessary for its effective use in concrete and indeed, various washing, chemical and thermal treatments have been explored in the succeeding sections, with the aim of collectively reducing the potentially damaging constituents such as metallic aluminium, chlorides, sulfates and organic matter.

4. USE AS AN AGGREGATE COMPONENT

4.1 Mortar

Municipal incinerated bottom ash has been used in mortar mixes as a component of sand ranging up to 100%. Samples were sieved to the appropriate grading and a number received further treatments involving ferrous and non-ferrous separation (Almeida and Lopes, 1998; Ferraris et al, 2009; Tang et al., 2015) washing (Kuo et al, 2015; Rashid and Frantz, 1992; Saikia et al., 2008, Saikia et al., 2015; Zhang and Zhao, 2014) and thermal treatment (Ferraris et al., 2009; Saikia et al., 2015).

The fresh properties of mortar with MIBA as an aggregate component are described in Table 2. Mixes achieved the target consistence, though compared to the control, reductions in the flow were evident or higher water contents were required to achieve equivalent consistency. To account for its higher absorption properties, MIBA should be added in a saturated surface dry state. These absorption properties did however reduce the bleeding and susceptibility to segregation. The lower specific gravity of the ash also resulted in a more lightweight mortar. The setting time of mortars has been shown to decrease with MIBA. This was attributed by Cheng (2011) to a quicker lime reaction and the contribution of the material to tricalcium aluminate formation.

Moving on to the hardened properties, the effect of MIBA as a fine aggregate replacement on the 28 day mortar compressive strength is examined in Figure 4. In addition to the standard processing and sieving, a number of further washing, chemical and thermal treatments (result shown as dotted lines in Figure 4) have been implemented to upgrade the performance. It is evident that, with one exception (Pavlik et al., 2011), MIBA led to reductions in strength, with losses ranging from 2-30% per 10% replacement level. The reason for the strength improvement from Pavlik et al. (2011) is unclear, though the results appear unreliable. The higher strength performance of these MIBA mixes was also inconsistent with the corresponding lower bulk density and higher porosity results, compared to the control.

Table 2: Effect of MIBA as a fine aggregate component on the fresh properties of mortars

REFERENCE	RESULTS
Consistence (Workability)	
Cheng (2011)	MIBA sieved < 4.75mm. With 10-40% MIBA as a sand replacement, achieved target flows in the 100-135mm range, though decreased from 131mm (0% MIBA) to 101mm (40% MIBA).
Rashid and Frantz (1992)	MIBA sieved, washed, used as a complete sand replacement. Flows equal to the control achieved with MIBA, though more water was needed (appr. 300l with MIBA, 200l with sand).
Fresh Unit Weight	
Cheng (2011)	MIBA sieved < 4.75mm and replaced 10-40% of sand. Fresh unit weight reduced from 2248 kg/m^3 (control) to 1986 kg/m^3 (40% MIBA) due to lower sg of MIBA (2.16) versus sand (2.69).
Setting Behaviour	
Cheng (2011)	MIBA sieved < 4.75mm and replaced 10-40% of sand. Both initial and final setting times reduced with increasing MIBA content, curiously attributed partly to higher C_3A in MIBA.
Stability	
Cheng (2011)	MIBA sieved < 4.75mm and replaced 10-40% of sand. Bleeding reduced from 0.1988 mL/cm^2 (control) to 0.0443 mL/cm^2 (40% MIBA), due to the higher absorptive properties of the ash.

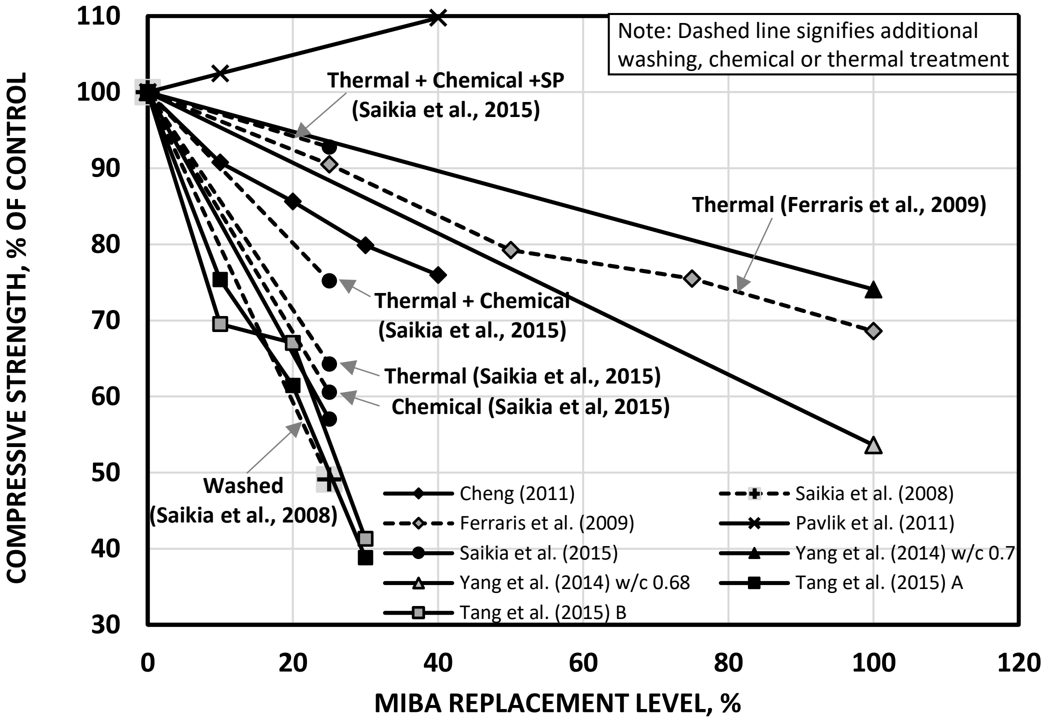

Figure 4: Effect of MIBA as a fine aggregate component on 28 day mortar compressive strength

Ensuring that minimal organic matter is present in MIBA and that its high absorption properties do not compromise the cement hydration appear to be the most important factors in limiting the strength reductions. Using MIBA samples with high LOI values of 10.2 and 12.1%, large strength losses were incurred (Saikia et al, 2008 and Saikia et al., 2015). Washing with water and Na_2CO_3 led to minor improvements in performance, contributed by reduced sulfates, chlorides and aluminium contents. However, thermal treatment was more effective in reducing the organic fraction in MIBA and consequentially further improving the strength. Tang et al. (2015) attributed large strength losses to the incomplete cement hydration due to more water being absorbed by MIBA. Superplasticizer can be added to counteract this behaviour, as was done successfully by Saikia et al. (2015), or this can also be limited by adding the MIBA aggregates in a saturated surface dry state.

The compressive strength data suggests that for widespread use of MIBA as an aggregate in concrete related applications, processing may be required and the extent of the treatment needed will be influenced in particular by the organic fraction present in the material.

Findings on the remaining properties of mortars incorporating MIBA as an aggregate are as follows:

Flexural strength – results mirrored the compressive strength performance, with MIBA leading to reduction in strength (Yang et al., 2014; Tang et al., 2015), though again, in one case (Pavlik et al., 2011/2012) strength improvement with MIBA was achieved.

Young's Modulus – reduction of 18-25% with 40% sand replacement, which can be attributed to the higher porosity of the MIBA aggregates (Pavlik et al., 2011/2012).

Permeation properties – data from Pavlik et al. (2011/2012) was somewhat at odds, as reductions in absorption and diffusivity were incurred with MIBA, despite the mortar mixes having higher porosities. Results for other MIBA samples (Kuo et al., 2015) were more consistent, with increases in porosity, absorption and permeability arising from the sand replacement.

Chlorides and sulfates – though not measured in the mortar mixes, the chemical treatment has been effective in reducing the Cl^- and SO_4^{2-} in MIBA (86% and 78% reductions respectively, with 0.25 M Na_2CO_3) (Saikia et al., 2015).

Expansion – the volume of mortar mixes containing up to 40% MIBA as aggregate were similar to the control mixes, suggesting that with MIBA in granular form, the reaction between the metallic aluminium and cement is not significant (Saikia et al., 2015).

4.2 Concrete

The bottom ash has been used commonly to a similar extent as both fine and coarse aggregate and to a limited degree as all-in aggregate in concrete mixes. In the fresh state, the effect of MIBA as a replacement of sand and gravel on the mix consistence is presented in Figure 5. These samples have been sieved to the required grading and at times additional washing (Dhir et al., 2002; Van der Wegen et al., 2013; Zhang and Zhao, 2014) and metal extraction (Dhir et al., 2002) treatments.

As a fine aggregate component, with the same water content as the control, MIBA led to significant reductions in the consistence of concrete measured as slump (Figure 5 (a)). This resulted in step downs from S2 to S1 slump categories in BS 8500 (2015) at times, and perhaps indicates that limiting its use to partial sand replacement may be more practical. However, as a coarse component, Figure 5 (b), the slump achieved with MIBA has been comparable to the controls. The lower specific surface area and absorption properties of the coarser fraction of MIBA meant that the negative effects on the concrete consistence are limited.

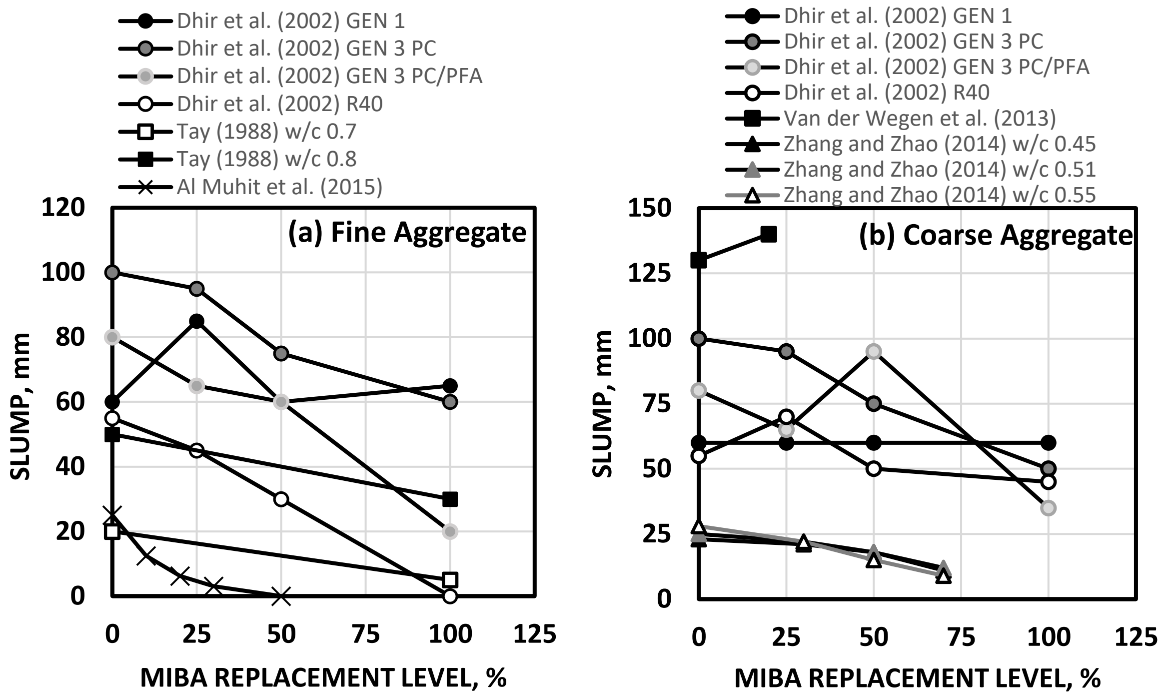

Figure 5: Effect of MIBA on the workability of concrete as (a) fine aggregate and (b) coarse aggregate

In terms of concrete stability, mixes containing MIBA as fine and coarse aggregates have been found to be cohesive, with no segregation problems (Dhir et al., 2002). Indeed, as a replacement of 20% of the coarse aggregate, bleeding reduced slightly from 1.6 to 1.1% compared to the control (Van der Wegen et al, 2013), due to the higher absorptive properties of the ash and the associated higher water retention.

As both a complete fine and then coarse aggregate replacement, no delays in the setting times were evident (Dhir et al., 2002). In contrast, as a replacement of 20% of the coarse aggregate and then the coarse + fine aggregate with washed MIBA, Van der Wegen et al. (2013) reported large delays of one and three hours, respectively, in the initial setting times. However, it should be noted that the control mix without MIBA already had a prolonged setting time of 500 minutes. The reasoning for this lengthening in the setting times is not stated, though may be due to interference from the zinc and lead present in the ash.

The effect of MIBA on the 28 day compressive strength performance is presented in Figure 6 (a) as fine aggregate and (b) coarse aggregate components. As a sand replacement, MIBA led to large strength losses, particularly with just standard processing and sieving. Washing and chemical (1 mol/l NaOH solution) treatments led to improvements by diminishing the inhibiting organics, salts and metals in the ash, enhancing its prospects for potential use, though perhaps more suitably as partial component in small components.

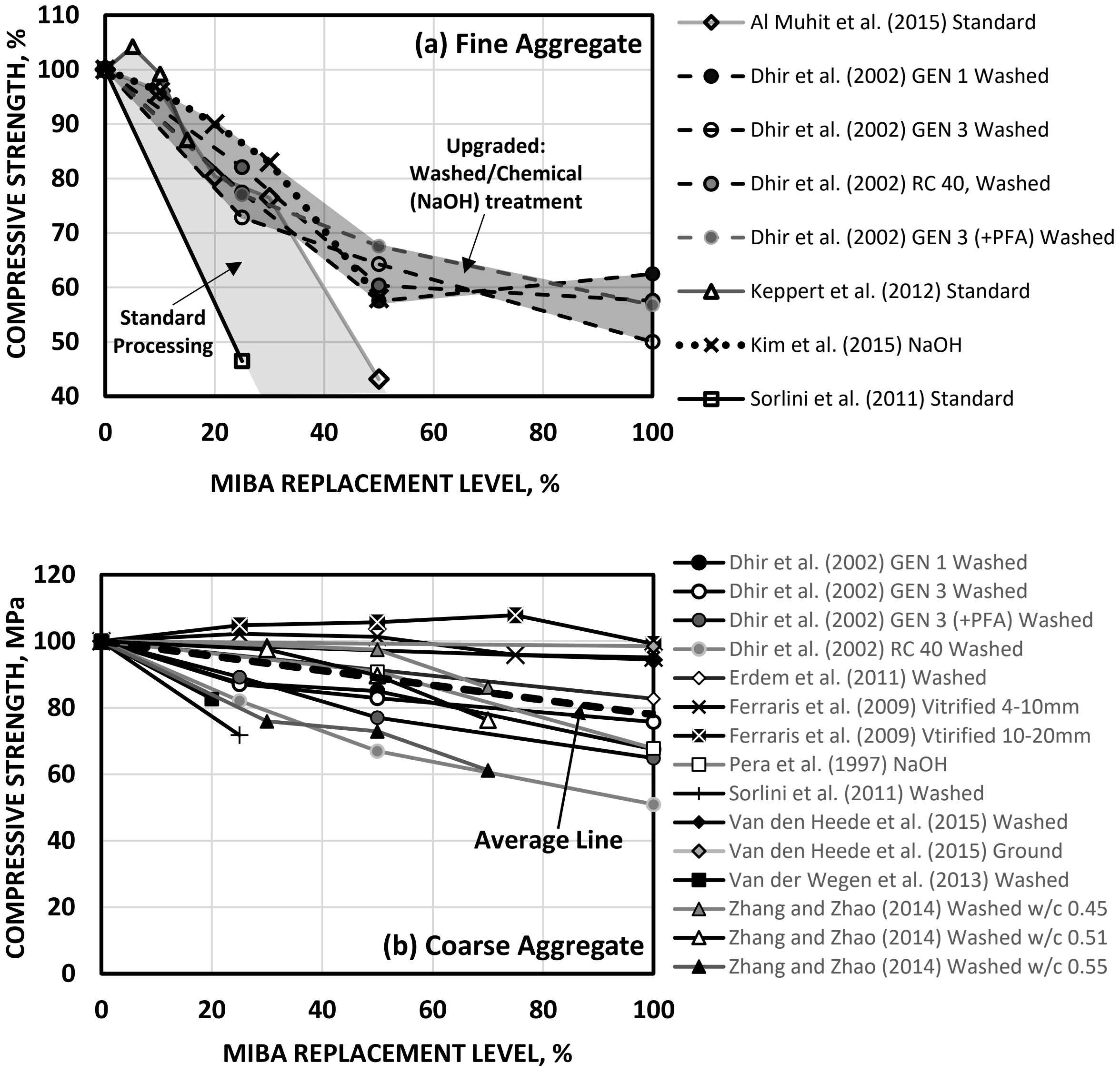

Figure 6: Effect of MIBA on the 28 day concrete compressive strength as (a) fine aggregate and (b) coarse aggregate components

As a coarse aggregate, the strength reductions with MIBA have been notably less, compared to as a fine aggregate, resulting in an average decrease in the 28 day concrete compressive strength of 5% per 25% MIBA content. It has been previously found that the coarse fraction of the ash has lower absorption properties than the fine fraction (section 3.4) and as such, it may have a smaller effect on the water movement and consequentially the hydration reaction and strength performance, depending on the moisture condition of the aggregate when added to the mix. The higher concentration of sulfate and chloride salts and metals lead, aluminium and zinc in the finer fraction of MIBA may also be factors in hindering strength development.

Washing has been again frequently incorporated as part of the MIBA pre-treatment procedure and from additional data (Dhir et al., 2002; Paine, 2002; Zhang and Zhao, 2014) was shown to lead to large improvements in strength. However, the vitrification treatment was the most effective, as is evident in Figure 6 (b) (Ferraris et al., 2009), producing compressive strengths in excess of the control mixes.

In concrete mixes with varying target characteristic strengths from 10-40 MPa (GEN 1, GEN 3 and R40, Dhir et al., 2002), the rate of strength reduction with MIBA was similar. Yu et al. (2014) also achieved compressive strength of 70 MPa, without fibres, and 115 MPa with steel fibres, using MIBA as a sand replacement. These results suggest that the ceiling strength of MIBA should not be a restriction. Indeed, failure mode testing by Al Muhit et al. (2015) indicates that as the MIBA content increases, the cement-aggregate bond fails before the aggregate crushes.

As a combined fine + coarse aggregate replacement, limited testing has been undertaken (Afriani et al., 2001; Van der Wegen et al., 2013), though the compressive strength results suggest that the MIBA replacement should be limited to low contents, in order to avoid excessive losses on par with the cumulative reductions evident in Figure 6 (a) and (b).

Tensile strength has generally been found to decrease with increasing MIBA contents as fine and coarse aggregate components in a similar manner to the compressive strength (Dhir et al., 2002; Van der Wegen et al., 2013). Indeed, the relationship between tensile and compressive strength for mixes containing MIBA is comparable to empirical relationship between these two parameters in Eurocode 2 (EN 1992-1-1, 2004). Flexural strength has been examined in a number of non-standard concrete applications: fibre reinforced concrete as fine (Yu et al., 2014) and coarse (Erdem et al, 2011) aggregate components and earth moist concrete as coarse aggregate components. In these application types, the roughness and irregularity of the MIBA particles was reported to have an overall beneficial effect on the flexural resistance, in particular in combination with the fibres.

On the deformation properties, the elastic modulus of concrete mixes have been found to decrease with MIBA as fine (Dhir et al., 2002; Dhir et al., 2011; Paine, 2002) and coarse (Van der Wegen et al., 2013; Zhang and Zhao, 2014) aggregate. Elastic moduli of mixes (Dhir et al., 2002) were close the typical ranges outlined in EN 1992-1-1 (2004) corresponding to the target characteristic cube strength with MIBA as a coarse aggregate replacement, though dropped below this range for fine aggregate replacement levels above 25%.

Drying shrinkage results with MIBA as a fine and coarse aggregate are presented in Table 3. Testing after time periods of 200 days and 1 year, Dhir et al. (2002) and Van der Wegen et al. (2013) reported increases in shrinkage with increasing MIBA contents. This can be attributed to the greater porosity and absorption of MIBA, resulting in the retention of higher quantities of water that eventually evaporates over time and causes shrinkage. The remaining study (Pera et al., 1997) reported equal or lower shrinkage in concrete mixes with the ash, albeit at a much shorter test age (14 and 28 days). However, it is notable that the absorption of the MIBA used in this concrete mix, measured at 2.4%, is at the very bottom of the range reported for MIBA (see section 3.4).

Table 3: Effect of MIBA as a fine and coarse aggregate on the concrete drying shrinkage

PUBLICATION	TEST	MIBA, %	SHRINKAGE, %	
Fine Aggregate Replacement				
Dhir et al. (2002)	GEN 3: Equal cement and water mixes air cured at 20°C at 55% RH for 200 days	0	-0.058	
		25	-0.087	
		50	-0.083	
		100	-0.107	
	GEN 3: Equal strength mixes air cured at 20°C at 55% RH for 200 days	0	-0.058	
		25	-0.098	
		50	-0.101	
		100	-0.11	
Coarse Aggregate Replacement				
Dhir et al. (2002)	GEN 3: Equal cement and water mixes air cured at 20°C at 55% RH for 200 days	0	-0.058	
		25	-0.07	
		50	-0.073	
		100	-0.082	
	GEN 3: Equal strength mixes aired cured at 20°C at 55% RH for 200 days	0	-0.058	
		25	-0.067	
		50	-0.07	
		100	-0.133	
Van der Wegen et al. (2013)	After 1 year. Test conditions unknown	0	-0.36	
		20	-0.39	
			Drying period	Wetting period
Pera et al. (1997)	14 day drying (20°C at 50% RH) and wetting (in water at 20°C) cycles	0	-0.03	-0.01
		50	-0.03	-0.01
		100	-0.025	-0.005

Limited testing on creep yielded values of 0.31 and 0.32%, respectively, after 1 year, for the control and mix containing washed MIBA as 20% of the coarse aggregate (Van der Wegen et al., 2013). This suggested that MIBA, at this low replacement level, did not significantly alter the concrete creep behaviour.

The absorption properties of concrete mixes have been found to increase with increasing MIBA contents, both as fine (Al Muhit et al., 2015; Dhir et al., 2002) and coarse (Dhir et al., 2002; Van den Heede et al., 2015) aggregate components, due to the material's rough particle surfaces and high porosities. Initial surface absorption results (BS 1991: Part 5, 1970) from Dhir et al. (2002), were found to remain within the range expected for normal concrete, for MIBA contents up to 25%. Increases in absorption from 11% (control mix) to 16% (up to 50% fine aggregate replacement) and from 0.7% (control) to 6% (100% coarse aggregate replacement) have been reported by Al Muhit et al. (2015) and Van der Heede et al. (2015), respectively.

The increase in absorption raises questions about the effect of MIBA on the concrete durability and the performance in this regard is examined below, covering hydrogen gas expansion, chloride corrosion, sulfate attack, carbonation resistance, freeze thaw, alkali silica reaction and acid attack.

Hydrogen gas expansion: damaging expansive reactions were evident using MIBA samples subjected to just standard sieving treatment (Al Muhit et al., 2015, Dhir et al., 2002). As such, metal extraction, washing and chemical treatments have been frequently required to minimize the hydrogen expansion by reducing the metallic aluminium content or stabilization by exhausting the expansive reactions before use. Measurement of the volume of hydrogen gas evolution and metallic aluminium content by Kim et al., (2015), showed effective reduction of both parameters after a chemical treatment with 1 mol/l of aqueous NaOH.

Chloride corrosion: the chlorides present in the as-produced MIBA is problematically high for its use in concrete and indeed, Valle-Zermeno et al. (2015) reported that corrosion risk is very high using weathered MIBA with steel rebar. Washing treatments have been commonly implemented to reduce the chloride content of the ash (e.g. Chen and Chiou, 2007; Dhir et al., 2002 and Van der Wegen et al., 2013). In the last study, the chloride diffusion coefficient also increased from 13.6 to 18.0 x $10^{-12}m^2/s$ with washed MIBA as 20% of the coarse aggregate. However, the effect of MIBA on this parameter will be significantly less than the impact of the cement type, as cements with high proportions of GGBS and PFA can be selected to improve chloride resistance (Van der Wegen et al., 2013). Further research would be useful to clarify the performance of washed MIBA in reinforced concrete mixes including with the above cement types.

Sulfate attack: the sulfate content of MIBA also reduces as part of the chemical and washing treatments. It was found that no expansion due to sulfate attack was evident when measuring after 200 days, with concrete containing 25, 50 and 100% MIBA as fine aggregate (Dhir et al., 2002, Paine, 2002).

Carbonation resistance: Carbonation depth was found to decrease from 3.5 mm for the control to 2.6 mm with 20% washed MIBA as coarse aggregate. It was reported that the higher amount of water absorbed by MIBA was beneficial in slowing the carbonation rate in the concrete mix. (Van der Wegen et al., 2013).

Freeze-thaw: freeze thaw resistance tests (CDF and CIF tests) undertaken with 20% MIBA as coarse aggregate showed improvements in the durability of the concrete mixes. This is due to the higher porosity associated with MIBA, as the void spaces effectively act as air entrainers. Concrete containing 10% MIBA as fine aggregate also demonstrated good frost resistance, with no decreases in strength or integrity after sustaining 125 freezing cycles (Keppert et al., 2012).

Alkali-silica reaction: glass constituents of MIBA may be susceptible to alkali silica reaction under certain conditions in concrete, though no significant evidence of deleterious action of silicate gel expansion was reported from laboratory and field testing with MIBA as coarse aggregate by Muller and Rubner (2006). In contrast, the expansion measured with MIBA as a complete coarse aggregate, in accordance with the modified Oberholster test, greatly exceeded the 0.1% limit that represents potential alkali-silica reaction sensitivity (Van den Heede et al., 2015). However, it remains to be confirmed if this was due to alkali-silica reactivity as the control limestone blend also exceeded the 0.1% threshold.

<u>Acid attack:</u> after cyclic exposure to latic and acetic acid, it was found that concrete mixes with washed MIBA as the coarse aggregate had a lower overall mass loss than the control limestone mix. However, visual inspection revealed that MIBA mixes were left with rougher outer surfaces and more heterogeneous damage compared to the smoother more uniformly damaged control mixes (Van den Heede et al., 2015).

4.3 Masonry Blocks

Use of MIBA in masonry blocks is an intriguing option, with a large potential market available and typically less demanding strength requirements. The processing of MIBA, mix designs and applications types that have explored the application of MIBA in blocks are described in Table 4. The material has been used as fine, coarse and all-in aggregate components in a range of masonry block applications, including full scale case studies (Breslin et al, 1993; Wiles and Shephard, 1999). Pre-treatment of MIBA typically involved size separation and metal removal, though one case implemented a plasma melting process, primarily due to environmental concerns (Katou et al., 2001). A number of additional studies using combined municipal solid waste bottom ash and fly ash in concrete blocks have also been carried out (Nishigaki, 1996; Nishigaki, 2000; Environment Agency, 2002; Rashid and Frantz, 1992).

Table 4: Description of the work undertaken with MIBA in masonry blocks

PUBLICATION	PROCESSING	MIX DESIGN	APPLICATION
Berg (1993)	Screened	MIBA as aggregate	Concrete masonry unit
Berg and Neal (1998a)	Sieved, ferrous removal, washing, stockpiled	MIBA as 65 and 100% sand replacement.	Concrete masonry unit
Berg and Neal (1998b)	Sieved, ferrous & non-ferrous removal, stockpiled	MIBA as 65% sand replacement	Concrete masonry unit

Breslin et al. (1993)	-	MIBA as aggregate	Case studies: artificial reef, shore protection blocks
Ganjian et al. (2015)	Sieved, ground to 4 and 6 mm size fractions	Replacement of 4mm and 6mm fractions	Concrete paving blocks
Holmes et al. (2016)	Sieved as fine aggregate	MIBA as 10-100% of fine agg.	Concrete masonry unit
Jansegers (1997)	Screened, sieved, ferrous and non-ferrous removal, air separation, aged	MIBA as complete gravel substitute	Hollow building stones
Katou et al. (2001)	Screened, ferrous removal, plasma melted	MIBA slag as fine agg (43% of overall mix)	Interlocking block
Lauer (1979)	-	Aggregate	Concrete masonry unit
Roethel and Breslin (1995)	-	55% MIBA as agg (of overall mix)	Hollow concrete masonry blocks
Siong and Cheong (2004)	As-produced	MIBA as all-in agg, 50-69% of overall mix	Non-structural blocks
Vu and Forth (2014)	Separated into 5-10mm and <5mm sizes	40:60 ratio MIBA:PFA as aggregate-filler	Masonry units with blended organic binders
Wiles and Shephard (1999)	-	MIBA as aggregate	Case studies - blocks in walls, boathouse, artificial reef, curbing, revetments, facades

The findings on the performance of these concrete masonry units incorporating MIBA are presented as follows:

Unit Weight: The density of the concrete blocks decreased with the inclusion of MIBA (Berg and Neal, 1998a; Berg and Neal, 1998b; Ganjian et al., 2015; Holmes et al, 2016; Lauer, 1979; Siong and Cheong, 2004). The ash itself has a lower specific gravity (average of 2.32, Section 3.2) than the natural aggregate and its irregular particle surfaces and high porosity can also effect the volumetric filling during moulding and, as such, decrease the dry unit weight. Modification of the cement type to incorporate fly ash and the inclusion superplasticizer have been shown to lead to increases in the mix density, due to improved volumetric filling during moulding (Berg and Neal, 1998a). Despite the reductions in density, products with MIBA as aggregate generally exceeded the lightweight classification and were categorised as medium-weight blocks (Berg and Neal, 1998b; Lauer, 1979).

Strength: Blocks with MIBA as aggregate exhibited lower compressive strengths, or tensile strengths for paving blocks, compared to natural aggregate units. As outlined previously, using fly as part of the cement blend and superplasticizer additions improved the unit weight and consequentially the compressive strength. The use of 35% sand alongside the MIBA yielded a 50% strength increase due to improved grading (Berg and Neal, 1998a), whilst Holmes et al. (2016) considered that 20% substitution of the aggregate would be the optimal replacement level. However, target strengths are generally low in masonry applications and MIBA mixes have achieved respective requirements in non-load bearing units (Siong and Cheong, 2004), load bearing units (Berg, 1993; Berg and Neal, 1998a; Siong and Cheong, 2004), paving units (with fibre addition) (Ganjian et al., 2015) and interlocking blocks (MIBA slag) (Katou et al., 2001).

Absorption: Expected increases in water absorption have been evident with MIBA as aggregate in blocks. To satisfy the target maximum absorption value of 12% given in ASTM C90-11b for loadbearing masonry units, the MIBA fine aggregate replacement needed to be limited to 20% (Holmes et al, 2016). Using MIBA to replace both the 4mm and 6mm aggregate size fractions in pavers, it was found that the finer fraction led to a large increase in absorption, whilst blocks with the coarser MIBA fraction (5.6% absorption) remained on par with the controls and below the 6% limit given in BS EN 1388 (2003). High water absorption values greater than 8% were reported by Jansegers (1997), though this was deemed acceptable as no associated durability problems were evident.

Shrinkage/Swelling: Despite high absorption, Jansegers (1997) reported no adverse shrinkage effects with MIBA as a complete coarse aggregate substitute in blocks. MIBA blocks produced by Berg and Neal (1998b) satisfied the ASTM C331 drying shrinkage requirements and indeed achieved better shrinkage performance than lightweight concrete masonry units containing commercial aggregate.

Pop-outs: Pop-outs and spalling in concrete blocks containing MIBA have been reported Berg and Neal (1998b) and Wiles and Shepard (1999). In both cases this was attributed to the corrosion of ferrous metals present in MIBA and this issue can be overcome by removing the ferrous metals during standard magnetic separation treatment of MIBA.

Fire resistance: The fire resistance testing evaluated the ability of the MIBA blocks to retain structural integrity during a fire and their resistance to a hose stream. MIBA blocks compared favourably with the standard concrete blocks containing natural aggregate (Breslin et al., 1993).

Freeze-thaw resistance: The freeze thaw resistance of blocks produced by Berg and Neal (1998a), containing MIBA as aggregate, was on par with commercial concrete masonry units and satisfied ASTM C90 requirements for loadbearing masonry units. Similar good performance was achieved with MIBA as coarse aggregate in hollow building stones (Jansegers, 1997) and as the 4 and 6 mm aggregate size fraction in paving blocks, though as both the 4+6 mm fraction, the BS EN 1338 (2003) requirement was not satisfied.

Slip resistance: Using MIBA as the 4, 6 and 4 + 6mm aggregate size fractions in concrete paving blocks, all products demonstrated excellent slip resistance, classified as having extremely low potential for slip, according to the classifications in BS EN 1333 (2003) (Ganjian et al., 2015).

Appearance: MIBA blocks have been compatible with interior wall renderings with no unsightly spots, efflorescence, flaking or blisters (Jansegers, 1997). However, ferrous particles in MIBA can lead to staining, though this can be nullified by implementing the standard magnetic ferrous metals removal treatment (Berg and Neal, 1998b).

4.4 Lightweight Aggregate Production

Lightweight aggregate have been produced from the thermal treatment of MIBA. The full process begins with pre-treatment of the ash, typically involving aging, ferrous and non-ferrous removal and sieving, followed by mixing with various combinations of PFA, clay, sand and cement. This blend is then ground, pelletized with water additions and sintered to produce a porous low density specimen with hard outer surface. Details of the mix constituents and the maximum sintering temperatures used are given in Table 5.

Table 5: Mix constituents and maximum sintering temperature used in the production of MIBA lightweight aggregate

PUBLICATION	MIX CONSTITUENTS	SINTERING TEMP, °C
Almeida and Lopes (1998)	30% MIBA, 10% PFA, 30% sand, 15% cement, 10% clay	-
Bethanis (2007)	40% MIBA, 60% PFA. 40% MIBA, 50% PFA, 10% clay	1100
Bethanis and Cheeseman (2004)	40% MIBA, 60% PFA, with 0-12% activated carbon	1040-1100
Bethanis et al. (2002)	MIBA only	1020-1080
Bethanis et al. (2004)	MIBA only	1080
Cheeseman et al. (2005)	MIBA only	1000-1080
Cioffi et al. (2011)	60-80% MIBA, 10-30% cement, 7-30% lime, 13-27% PFA	-
Qiao et al. (2008)	80% MIBA, 20% cement	-
Rebeiz and Mielich (1995)	MIBA only	1000
Wainwright (1981)	95% MIBA, 5% clay	950-1000
Wainwright (2002)	82% MIBA, 18% clay. 90% MIBA, 10% clay	1100-1230
Wainwright and Boni (1983)	85% MIBA, 15% clay	975
Wainwright and Cresswell (2001)	82% MIBA, 18% clay. 90% MIBA, 10% clay	1100-1230
Wainwright and Robery (1991)	MIBA with clay	-
Wainwright and Robery (1997)	MIBA with clay	-
Wang et al. (2003)	MIBA only	400-600

The maximum sintering temperature generally varied been 1000-1200°C, with the exception of Wang et al. (2003), who selected temperatures from 400-600°C due to concerns of cracking at higher temperatures. However, this cracking problem could perhaps be alleviated with the use of a binder such as clay or cement, along with MIBA, as has been done in some other studies.

Of further interest, Gunning et al. (2009) explored the potential to react carbon dioxide with MIBA to produce carbonated aggregates with characteristics similar to lightweight aggregates. It was found that the reactivity of MIBA was low and as such, the material was not included in the subsequent testing.

A key requirement in lightweight aggregate production is to induce the expansive reactions that results in lightweight properties, whilst maintaining a balance between adequate strength properties and low absorption. Particle density results for lightweight aggregate produced with MIBA are presented in Figure 7. The EN 13055-1 (2002) limit of 2000 kg/m^3 for lightweight aggregate is marked for reference, along with the typical density of commercial Lytag.

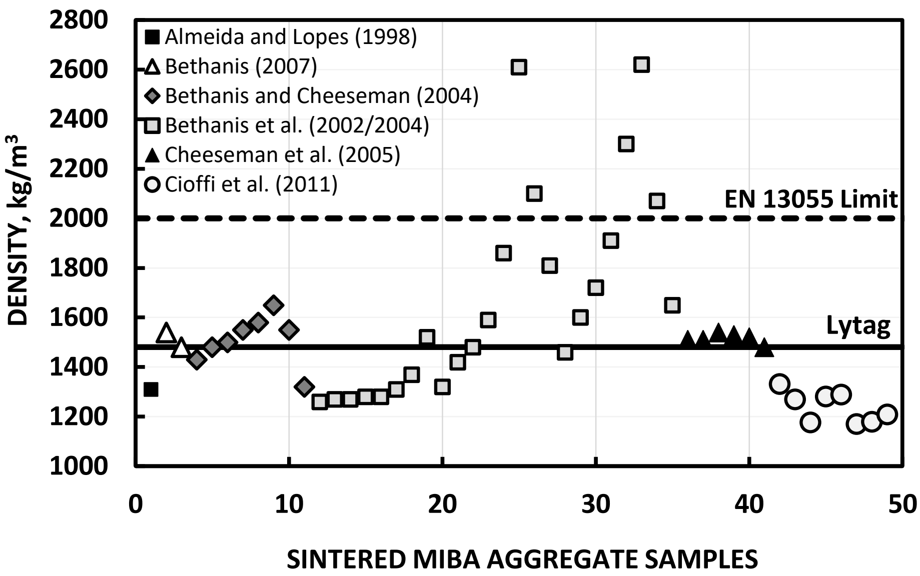

Figure 7: Particle density of sintered MIBA lightweight aggregates

Aside from a few exceptions from Bethanis et al. (2002/2004), the MIBA aggregates fall within the EN 13055-1 (2002) limits and most are similar to the density of Lytag. The main influencing factors are the maximum sintering temperature and the fineness of the mix after grinding. Testing at maximum temperatures from 1020-1110°C, it was found that the peak density was achieved at 1080°C, after which the density reduces dramatically due to the formation of large pore spaces. The MIBA aggregate specimens exceeding 2000 kg/m^3 (in Figure 7) were only produced when sintering temperatures close to the peak density temperature (1070-1090°C), were combined with intensive grinding.

Additional bulk density results from 820-1060 kg/m^3 have been recorded for lightweight aggregate produced with MIBA mixes (Bethanis, 2007; Bethanis and Cheeseman, 2004; Wainwright, 2002; Wainwright and Boni, 1983; Wainwright and Cresswell, 2001), which is above the typical Lytag range of 700-800 kg/m^3, though within the EN 13055-1 (2002) lightweight aggregate classification threshold of 1200 kg/m^3.

Due to their inherent porosity, the water absorption properties of lightweight aggregate are generally significantly higher than normal weight aggregate, however, as is shown in Figure 8, the water absorption of the MIBA lightweight aggregates is mostly similar to the typical value for Lytag and well below the EN 13055-1 (2002) limit. The one exception that exceeded the EN 13055-1 (2002) limit, contained a activated carbon addition along with MIBA and PFA, which had the effect of further lowering the density, though also resulted in considerably higher water absorption, due to carbon decomposition (Bethanis and Cheeseman, 2004).

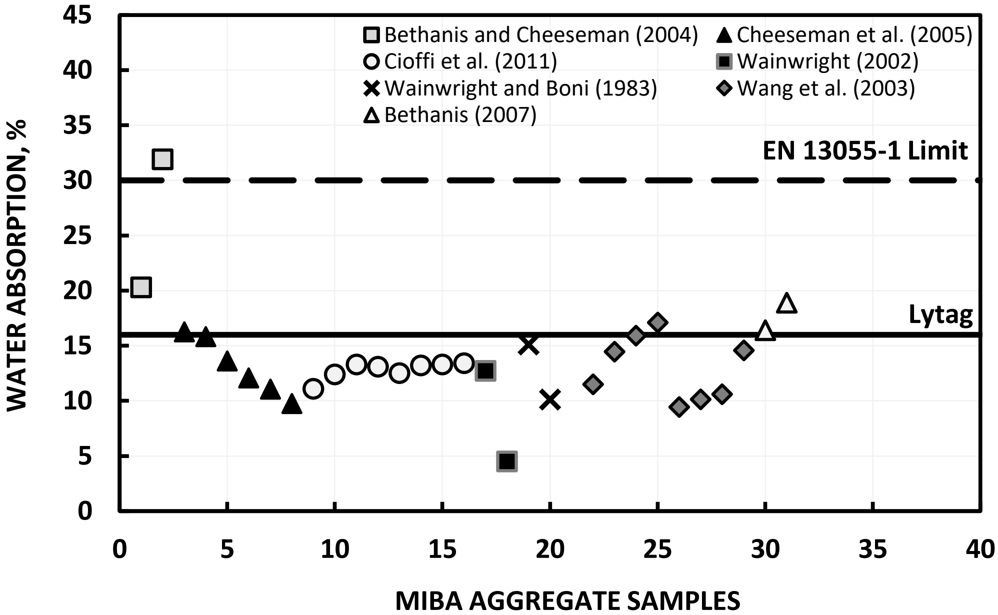

Figure 8: Water absorption of MIBA lightweight aggregates

Compressive strengths around 5 MPa were reported for the MIBA aggregate pellets produced by Cheeseman et al. (2005), compared to 7 MPa for Lytag. Values ranging from 1.9-4.5 MPa have been achieved in order of strongest-to-weakest with combinations of MIBA+cement, MIBA+lime and MIBA+lime+fly ash (Cioffi et al., 2011). The strength of the MIBA aggregate increased with increasing cement proportion, and as such, this binder can be added to boost the performance with MIBA to a level on par with Lytag. Unconfined compressive strengths (ASTM D2166, 1985) from 50-52 MPa were reported for compacted MIBA aggregate produced with lower sintering temperatures from 400-600°C (Wang et al., 2003). This MIBA aggregate was rated fit for its target use in permeable blocks.

4.5 Lightweight Aggregate Concrete

The use of a number of the above MIBA lightweight aggregates in concrete mixes has also been explored. An additional study by Dhir et al. (2002) examined the use of processed, washed, but un-sintered MIBA as a substitute for the 12-6mm sintered PFA aggregate fraction in lightweight concrete. The performance of these concrete mixes is described below.

Consistence – concrete with lightweight aggregate produced 80% MIBA+20% clay and 90% MIBA+10% clay showed remarkable improvements in the slump, increased to 95 and 135 mm, compared to 20 mm for the natural aggregate control (Wainwright and Cresswell, 2001). This was attributed to the smoothness of the particles after pelletization and sintering, yet the MIBA mixes still greatly out-performed the Lytag (10 mm slump) and PFA mixes (50mm slump). Consistent improvements in workability has also been evident in additional slump, compacting factor and Vebe tests compared to the natural aggregate and commercial lightweight aggregate mixes (Wainwright, 2002; Wainwright and Boni, 1983). The opposite behaviour was reported with un-sintered MIBA replacing the commercial lightweight aggregate (PFA), as a 33% drop in slump was incurred at the 100% replacement level.

Unit Weight – when replacing natural aggregate, concrete mixes containing MIBA-based lightweight aggregate incurred expected decreases in unit weight. Bulk densities from 1.71-1.82 g/cm^3 with MIBA, compared to 2.1 g/cm^3 with natural aggregate, and plastic densities from 2.0-2.1 g/cm^3 (MIBA), compared to 2.4 g/cm^3 (natural aggregate), have been reported by Qiao et al. (2008) and Wainwright and Boni (1983), respectively.

Absorption – the initial surface absorption of concrete mixes using un-sintered MIBA as a replacement of the sintered PFA aggregate have been tested (Dhir et al., 2002). Absorption values were notably lower in mixes with MIBA (0.2 – 0.4 ml/m^{2}s) compared to the PFA lightweight aggregate mixes (0.7 – 1.2 ml/m^{2}s).

Strength – reductions in compressive strength have generally been evident when comparing concrete mixes with MIBA to those with natural aggregate or Lytag. Using aggregate made from 80-90% MIBA + 10-20% clay, Wainwright (2002), Wainwright and Boni (1983), Wainwright and Cresswell (2001) reported 28 day compressive strengths that were 79-95% of the Lytag mixes. However, strengths 109, 113, 80 and 82% of the control natural aggregates concrete have been achieved with MIBA sintered at 600, 700, 800 and 900°C, respectively (Qiao et al, 2008). These higher strength results can be classed as abnormal and appear to be due to the faster setting behaviour observed for the MIBA concrete mixes, rather than superior aggregate strength. The combination of MIBA (40%), PFA (50-60%) and clay (0-10%) proved to be effective, achieving concrete strength on par with Lytag mixes and greater than double LECA mixes (Bethanis, 2007). With un-sintered MIBA, a compressive strength reduction of 15% was incurred when replacing the PFA lightweight aggregate (Dhir et al., 2002).

Elastic Modulus – using lightweight aggregate produced with 85% MIBA + 15% clay as a natural coarse aggregate substitute, concrete static modulus and dynamic modulus results varied from 12-15 kN/mm^2 and 20-22 kN/mm^2, respectively at 28 days. As expected, these values were significantly below the control natural aggregate mix, which varyied from 27-34 kN/mm^2 (static) and 41-46 kN/mm^2 (dynamic), respectively. Further results for mixes tested up to 1550 days, showed that MIBA did not affect the rate of development of the elastic modulus, but that the MIBA strength progression line was shifted down by 15-25 kN/mm^2 (Wainwright and Boni, 1983).

Shrinkage – tested after 250 days, the shrinkage strains of concrete mixes with 82-90% MIBA + 10-18% clay were on par with the Lytag mix, though the results were 54-72% higher than the natural aggregate mix, (Wainwright, 2002, Wainwright and Boni, 1983).

Creep – concrete creep strain increased with the use of lightweight aggregate produced using 85% MIBA + 15% clay, which was attributed to the lower elastic modulus of the MIBA aggregate (Wainwright and Boni, 1983). However, the subsequent creep coefficients (calculated based on creep strain, applied creep stress, static modulus of elasticity and the initial elastic deformation) for both MIBA and the control aggregate mixes were similar for concrete mixes stored in both dry and wet conditions (Wainwright and Boni, 1983).

4.6 Foamed Concrete

Foamed concrete is produced by pumping a pre-made foam into a mix of cementitious materials, fine aggregate and water. The end product is highly flowable, self-compacting, self-curing, lightweight, with low strength properties, and can be used in trench filling applications. Due to the high air content, there is less contact between particles and as such, the aggregate quality is less important. MIBA has been examined as a 50 and 100% of natural sand in foamed concrete mixes with target plastic densities of 1000 and 1400 kg/m^3 and cement contents of 300 and 400 kg/m^3 (Jones et al., 2005). The consistence and strength results are presented in Table 6.

Table 6: Foamed concrete properties with MIBA as a sand replacement (data from Jones et al., 2005)

TARGET DENSITY$_{PL*}$, kg/m^3	CEMENT, kg/m^3	MIX	SLUMP FLOW, mm	28 day cube strength, N/mm^2
1000	400	Control (100% sand)	650	1.3
		50% MIBA	695	1.2
		100% MIBA	720	1.4
1000	300	Control (100% sand)	715	0.8
		100% MIBA	640	1.1
1400	400	Control (100% sand)	625	4.2
		100% MIBA	430	3.8

*PL - plastic

The effect of MIBA on the foamed concrete consistence was somewhat mixed, with decreases in the slump flow evident in two out of three of the mix designs. It is noticeable that for the higher density and strength mix, the decrease in slump with MIBA became more pronounced. However, all MIBA mixes were above the 400 mm slump flow spread recommended to retain the desired self-flowing properties. The 28 day sealed-cured cube strength for mixes containing MIBA were quite similar to the natural sand mixes and were at the standard level for foamed concrete. In addition to the mechanical performance, it was also estimated that, based on savings on material costs and natural aggregate levies, the use of MIBA mixes could lead to savings of £9.10/tonne at that time (Jones et al., 2005).

5. CASE STUDIES

The practical utilization of MIBA in concrete related applications remains in the early stages, though most of the work undertaken has been in block production, in countries such as Japan, Spain, USA and in particular, the UK (Dunster and Collins, 2003; ISWA, 2006; IEABioenergy, 2000).

Blocks

- **Edmonton, UK – MIBA as block making material** (Environment Agency, 2002): Between 1998 and 2000, Ballast Phoenix supplied over 15,000 tonnes of MIBA to block-makers around the UK. It was estimated that over 5 million blocks could have been produced from this quantity, though a significant proportion would have been consumed through trial tests.
- **Dundee, UK – precast concrete blocks** (Dhir et al., 2002): Full scale demonstrations with MIBA as aggregate in concrete blocks. MIBA mixes had dry densities greater than the standard concrete block, as the ash replaced a lightweight aggregate. Compressive strength decreased with MIBA, though all products remained at a similar level to the control block. The drying shrinkage results were somewhat mixed, though again were not overly different to the standard block. The thermal conductivities of the MIBA blocks were similar or greater than the standard blocks.
- **Dundee, UK – precast lightweight thermal blocks** (Dhir et al., 2002): Full scale demonstrations with MIBA used as a 20% aggregate replacement in 100mm blocks and 50% aggregate replacement in 140mm blocks. The density and absorption of the MIBA blocks exceeded the limits outlined in BS 6073 (1981) for precast masonry units, though satisfactory compressive strengths and thermal conductivities were achieved.
- **Conscience Bay, Long Island, USA – blocks in artificial reef structure** (Wiles and Shephard, 1999): Blocks containing 85% MIBA + 15% Portland cement were used in this project undertaken in 1988. When examined in 1992, it was found that the MIBA blocks retained their original strength and were deemed to have performed effectively in challenging conditions.
- **Montgomery County, Ohio, USA, blocks in non-load bearing walls** (Wiles and Shephard, 1999): MIBA was used as aggregate in concrete blocks in outer walls in two buildings constructed in 1991 and 1992. Both walls were in good condition in 1997, however, a small amount of spalling was evident on the block surfaces in the first building, attributed to the ferrous metals in MIBA.

As this was identified early, it was rectified for the second building through more effective ferrous metal separation treatment.

- **Keilehaven, The Netherlands – paving blocks** (Chandler et al, 1997): 300,000 concrete paving blocks were produced in 1984, with up to 40% replacement of the coarse aggregate with the 5-8mm MIBA size fraction. This project was subsequently monitored and it was found that after five years of traffic loading, the MIBA paving blocks performed no differently to the standard blocks.
- **UK – dense and lightweight aggregate blocks** (Dunster, 2007): WRAP project in collaboration with industry, with MIBA used as aggregate in dense and lightweight aggregate blocks produced around the UK. It was reported that this work stopped due to problems with pop outs arising from non-ferrous particles that were not adequately removed during processing.

<u>Lightweight Aggregate</u>

- **Connecticut, USA – lightweight aggregate production** (Cosentino et al., 1995 from Plumley and Boley, 1990): Lightweight aggregate was produced at ABB Resource Recovery using MIBA blended with lime and water. The resultant product achieved the desired lightweight characteristics and MIBA was deemed fit for practical application as a lightweight aggregate.
- **Islip, NY, USA – commercial lightweight aggregate** (Wiles and Shephard, 1999): Lightweight aggregate called Rolite was produced using MIBA and Portland cement. This commercial process began in 1989, with hundreds of thousands of tons of MIBA used, including at Blydenburgh Landfill to construct a gas venting layer and as a lightweight fill material.

<u>Concrete</u>

- **Dundee, UK – ready mix concrete** (Dhir et al., 2002): full scale demonstrations with MIBA as 25% and 50% replacements of coarse aggregate. Superplasticizer was required in the MIBA mixes to achieve the desired workability. MIBA mixes were found to be cohesive and had good finishability. Compressive strength results were somewhat reduced, reaching 95% and 87% of the control at 28 days, using 25% and 50% MIBA, respectively.

6. CONCLUSIONS

As-produced MIBA contains particles up to 100mm, though is typically screened to remove the oversized fraction and further sieved for use as aggregate. MIBA has an average specific gravity of 2.32, though this decreases marginally after metal recovery treatment and increases after grinding. The irregularly shaped particles and porous microstructure led to high water absorption properties, averaging around 10%. The main oxides in MIBA are SiO_2, CaO and Al_2O_3, though the material contains potentially problematic amounts of sulfates, chlorides, metallic aluminium and organics that suggests that treatment is required for use in concrete.

As a fine aggregate in mortar, MIBA led to reductions in consistence, compressive strength, flexural strength and elastic modulus, compared to natural aggregate mixes, due to its higher porosity and absorption. Flow values have been maintained within the target range by using MIBA as a partial rather than complete fine aggregate. Loss of strength in mortars also indicated greater suitability of MIBA as a partial sand substitute. Minimizing the organic fraction in the ash is an important factor in limiting the strength losses and thermal treatment was the most effective method in achieving this, though preferably, the LOI of MIBA should be limited at the incineration stage. Washing with water or Na_2CO_3 were alternative treatments implemented to limit strength losses and improve durability by reducing the sulfate, chloride and metallic aluminium contents.

In concrete, MIBA has been used as both fine and coarse aggregate replacements. More favourable results were evident as a coarse component, with minor slump and strength reductions with treated MIBA, compared to the control. The data suggests that washing of MIBA is required, both to limit the strength loss and avoid negative durability effects stemming from expansion due to the metallic aluminium in MIBA and increased susceptibility to chloride and sulfate attack. Further research to clarify the durability of reinforced concrete containing treated MIBA, including the influence of various cement types, would be beneficial. Increases in the drying shrinkage and absorption of concrete was also evident due to the higher water retention associated with the porosity of MIBA, though this led to strong frost resistance properties.

As coarse and fine aggregate components in concrete blocks, MIBA led to reductions in unit weight, though the blocks generally exceeded the lightweight classification and were categorised as medium-weight. Despite compressive strength reductions with MIBA, the less onerous requirements for non-load bearing, load-bearing, paving and interlocking blocks were satisfied. However, to prevent excessive absorption properties, limiting MIBA to use a partial aggregate component is preferred. MIBA blocks displayed satisfactory drying shrinkage, fire resistance, freeze-thaw resistance and slip resistance. Pop-outs, spalling and staining arising due to ferrous metals in MIBA has been problematic at times, including in case studies, though can be overcome by ensuring effective removal of ferrous components during magnetic separation treatment of MIBA. A number of full scale demonstrations in the UK, USA and Netherlands have successfully produced large quantities of blocks using MIBA as aggregate.

Lightweight aggregates produced from the grinding, pelletizing and sintering of MIBA achieved the desired low density properties to satisfy the lightweight classification limit. Absorption properties of the MIBA aggregate were on par with Lytag, whilst compressive strength was marginally lower. As a natural aggregate replacement in concrete, MIBA lightweight aggregate led to improvements in the consistence, along with the expected decreases in the unit weight. The compressive strength of concrete was generally lower with MIBA aggregate compared to natural aggregate and Lytag mixes. The concrete elastic modulus decreased with MIBA, which contributed to higher creep strains.

However, the subsequently calculated creep coefficients for MIBA lightweight aggregate and natural aggregate mixes were similar. The shrinkage of MIBA mixes was comparable to Lytag mixes, though both exceeded the natural aggregate concrete.

As a sand replacement in foamed concrete, reductions in the slump flow were evident at times with MIBA, though all mixes retained the desired self-flowing properties. Compressive strength for MIBA and sand mixes were similar, with both at the standard low level required for foamed mixes. Initial testing with MIBA in this application has been promising and this appears to be an area in which further research could be productive.

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